Backpropagation Processing of GPS Radio Occultation Data

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Summary. We provide an assessment of the backpropagation (BP) method for processing GPS radio occultations using simulations as well as recent data from CHAMP and SAC-C. It is found that BP gives improved retrievals over the standard Doppler technique, even when multipath ambiguities are not completely removed. In addition, by being an amplitude-weighted algorithm, BP is robust in the presence of receiver errors that arise when signals with low SNR are tracked.

Keywords. *backpropagation, end-to-end simulation, lower troposphere, multipath, occultation, tracking error.*

1 Introduction

Radio occultations have long been used in the remote sensing of planetary atmospheres [1]. Recently, thanks to the availability of the GPS satellite constellation, similar techniques can be applied to provide vertical profiling of the Earth's atmosphere and ionosphere [2, 3, 4]. The GPS/MET experiment, which collected occultation data from April 1995 to February 1997, has already provided a wealth of interesting data for scientific analysis [5]. The currently operating CHAMP and SAC-C spacecrafts, equipped with the more advanced BlackJack GPS flight receiver, are capable of tracking deeper into the lower troposphere and have a combined throughput of about 300–400 occultations per day.

The "standard" Doppler retrieval method converts the excess phase measurements due to atmospheric refraction into the raypath's bending angle α as a function of impact parameter a. The relation $\alpha(a)$ is then integrated — via Abel inversion — to yield the vertical profile of the refractive index [1]. However, humidity gradients typically present in the lower troposphere could cause multiple signals to arrive at the receiver simultaneously. In this case, the retrieval algorithm infers multiple values of bending for the same impact parameter. To compute the Abel inversion integral, an *ad hoc* procedure needs to be applied to force $\alpha(a)$ to take on single values. This could result in substantial retrieval errors. To further complicate lower tropospheric retrievals, rapid signal variations and low signal strength associated with these sharp refraction layers could also pose significant tracking problem for the GPS receiver. Receiver tracking errors could further add to the retrieval biases [6].

In recent years, a number of "radioholographic" methods have been proposed that not only aimed to resolve the multipath problem encountered by the standard method but also to improve the vertical resolution of the retrievals [7, 8, 9, 10, 11, 12]. These methods use both the amplitude and phase of the received signal in reconstructing the ray structure of the refracted field. In this paper, we shall focus on the backpropagation method and provide an evaluation of the method based on simulated occultations as well as recent data collected by CHAMP and SAC-C.

2 Formulation

The backpropagation (BP) method takes the signal amplitude and phase received at the low earth observing (LEO) satellite and continue them backward in vacuum using diffraction theory (Fig. 1). By reducing the blurring effects of the forward propagation, the BP method has two very attractive advantages. First, it increases the vertical resolution of the retrieval. Second, it could unravel multipaths which cause retrieval errors in lower troposphere.

In 2-D, the scalar diffraction integral can be written, for backward propagation, as

$$u_{\mathrm{BP}}(\mathbf{r}) = \sqrt{\frac{ik}{2\pi}} \int_{\mathrm{LEO}} d\mathbf{r}' \left[\frac{\exp(-ik|\mathbf{r}-\mathbf{r}'|)}{|\mathbf{r}-\mathbf{r}'|^{3/2}} (\mathbf{r}-\mathbf{r}') \cdot \hat{n}(\mathbf{r}') \right] u(\mathbf{r}') \tag{1}$$

where $u(\mathbf{r}') = A(\mathbf{r}')\exp(i\phi(\mathbf{r}'))$ is the measured field at the LEO, $u_{\mathrm{BP}}(\mathbf{r})$ is BP field at $\mathbf{r}$, and $\hat{n}(\mathbf{r}')$ is the outward unit vector at the LEO. Equation (1) is derived by invoking the Kirchhoff approximation, which is valid if the radius of curvature of the LEO orbit is much larger than the electromagnetic wavelength [13]. As emphasized elsewhere [7, 8], the aim of the BP is not to reconstruct the field but the ray structure of the field at the BP "orbit." Thus BP in vacuum will not introduce any error in the Abel inversion.

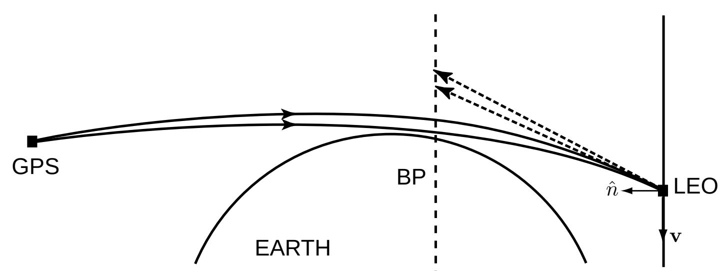

Fig. 1. Backpropagation geometry. Using diffraction theory, the rays are continued backward (i.e., towards the source) in *vacuum.*

To remove all multipath ambiguities, the BP orbit should be chosen such that it does not intersect with any caustics. However, without *a priori* knowledge of the atmospheric refractivity, it is not clear whether such an orbit exists or how it can be obtained. Moreover, because BP does not take into account of the atmosphere, rays that diverge at the LEO could very well converge at the BP orbit if we were to position it too far back. To avoid intersection with these so-called *imaginary caustics*, Gorbunov *et al.* [9] suggested a simple rule of thumb for the limb distance of the BP plane as $x_{\mathrm{BP}} = R_E \alpha_{\max}$, where R_E is the radius of curvature of the Earth and $\alpha_{\max}$ is the maximum bending angle. For typical occultation parameters, $x_{\mathrm{BP}} = 200$ km. Our testing shows that this choice works well for simulated occultations (see Sec. 3). Even in cases where BP does not completely remove all the multipaths, the method succeeds in improving the retrievals.

3 Backpropagation for Simulated Occultations

The simulated occultations are generated using the multiple phase screen (MPS) model, which represents the split-step solution of the parabolic wave equation [14]. The amplitude and phase recorded at the receiver plane can be converted to time series measurements and fed through the retrieval system as if they were from real occultations.

Sharp refractivity gradients in the lower troposphere lead to strong amplitude and phase fluctuations which could pose a problem for receiver tracking. This problem is particularly severe when critical, or nearly critical, refraction layers prevent most of the signal from ever reaching the receiver. The so-called flywheeling tracking strategy has been implemented on CHAMP and SAC-C occultations so that data can continue to be collected during periods of momentarily low SNR and allow the normal tracking loop to resume operation when the signal strength increases again. During the flywheeling mode, the model phase in the tracking loop is obtained based on the extrapolation of the observed phase just before the onset of flywheeling. To understand how well tropospheric retrieval algorithms perform on real data, it is important to incorporate realistic receiver tracking errors in simulated occultations. For this reason, we have developed the capability to process the simulated data through an identical copy of the BlackJack receiver which is on-board CHAMP and SAC-C. Such end-to-end simulations help us isolate the effects of the atmosphere from the receiver and provide a platform for improving retrieval as well as tracking algorithms.

For the results shown here, we use as input a radial refractivity profile that is derived from a radiosonde sounding. The profile shows a superrefraction layer at about 3 km, which causes the signal amplitude to drop to a very low value for an extended period of time (Fig. 2) and triggers the receiver flywheeling mode. In Fig. 3, we compare the standard and BP retrievals using data with and without receiver tracking. Several observations can be

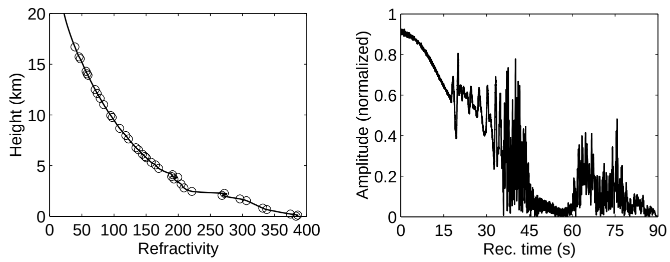

Fig. 2. Simulated occultation. *Left*: input refractivity profile shows a superrefraction layer at about 3 km in height. *Right*: received signal at the observation plane has an extended period of time where the amplitude remains small.

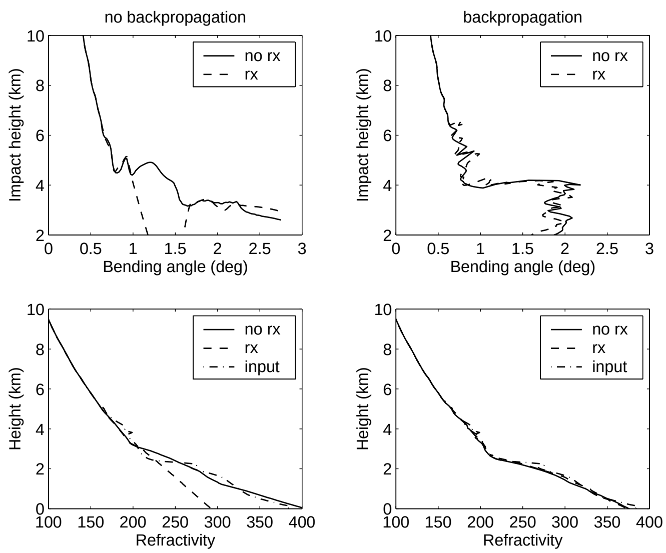

Fig. 3. Effects of receiver tracking on standard and BP retrievals as manifested in bending angle and refractivity. "no rx": MPS data with no receiver or perfect tracking; "rx": MPS data with simulated receiver tracking.

made from these comparisons: (1) Without BP and with perfect tracking, multiple values of the bending are deduced, resulting in significant retrieval errors below 3 km in altitude; (2) BP reduces the multipath ambiguities but does not eliminate them; (3) Without BP, tracking errors cause a substantial negative bias in refractivity; (4) BP is *nearly unaffected* by tracking errors. The last point is at first glance rather surprising since one would expect that the back-continuation of flawed data should still result in flawed retrievals. However, it can be observed from Eq. (1) that the BP integral involves a linear weighting by the signal amplitude. Thus the regions where the *worst* error occurs would contribute the *least* to the BP field.

4 Backpropagation on CHAMP and SAC-C Data

Several complications arise when the BP algorithm is applied to real occultation data. These issues and their corresponding solutions are discussed briefly here. (1) *Transmitter motion compensation.* The diffraction integral used in the BP method assumes time-harmonic waves. The slow time dependence in the transmitting satellite position must first be removed. This is done by transforming the satellite positions such that the transmitter is fixed at all times. The phase is adjusted to account for the straight-line path differences between the original satellite positions and the transformed satellite positions. (2) *Synchronization.* Each data point is associated with a receiver time tag t, which is used in relating the occultation tangent point to its geodetic location. However, such information is lost after BP is performed since each BP point is now associated with an artificial time tag t_{bp}. To relate t_{bp} back to t, we compare the BP impact parameter $a(t_{bp})$ with the impact parameter $a(t)$ from the standard retrieval. While some errors in a are expected from the standard retrieval in multipath regions, this will not seriously affect the determination of the tangent point coordinates. (3) *BP on L1 only*. L2 measurements have lower SNR and are affected by Anti-Spoofing; moreover, its amplitude data is currently stored only once every second. Since BP depends crucially on amplitude information, we apply BP on L1 data only. Ionospheric calibration is based on the BP L1 data and the non-BP L2 data.

We present BP retrievals for CHAMP and SAC-C occultations taken on September 30, 2001. Typical examples are shown in Figs. 4 and 5. In Fig. 4, BP is able to remove all multipath ambiguities and reduces the refractivity bias with respect to the profile obtained from the National Centers for Environmental Prediction (NCEP). In Fig. 5, BP differs very little from the standard retrieval, both of which exhibit a negative bias with respect to the NCEP profile. Mean refractivity differences relative to NCEP are shown in Fig. 6. It can be seen that the negative refractivity bias below 5 km is gener-

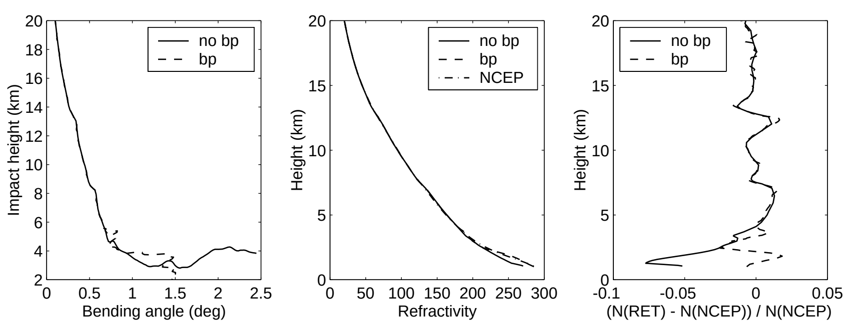

Fig. 4. An example showing improved retrieval with BP. SAC-C; occultation start time is 2001/09/30 06:14 UT.

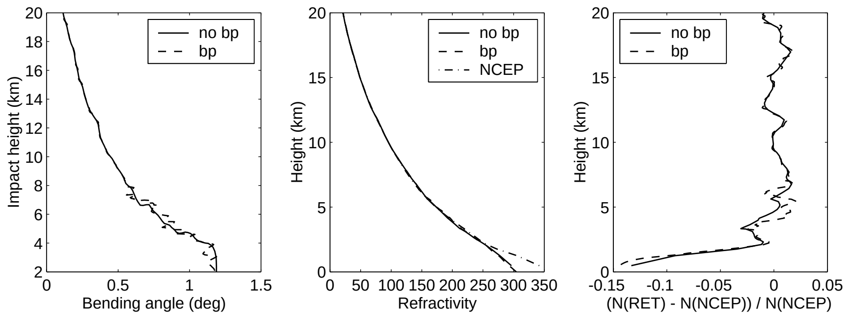

Fig. 5. An example showing no improvement in retrieval with BP. CHAMP; occultation start time is 2001/09/30 09:58 UT.

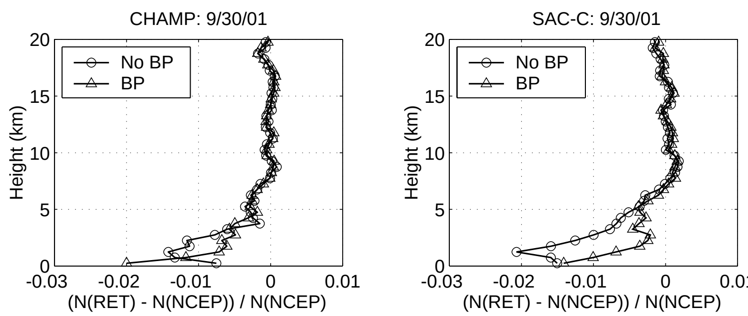

Fig. 6. Mean refractivity difference relative to NCEP based on one day of retrievals.

ally reduced by BP, especially for the SAC-C data. The remaining bias could be due to a number of factors, including the failure of BP to remove all multipaths, limitations of Abel inversion, premature termination of occultation tracking, as well as errors in numerical weather prediction models. More work is needed to quantify these various effects.

5 Conclusions

We have studied the backpropagation (BP) method on simulated occultations which incorporated realistic receiver tracking as well as on real data from CHAMP and SAC-C. From the simulations, it was found that BP did very well (but not perfectly) in removing multipath ambiguities that often plagued lower tropospheric retrievals. Moreover, BP was found to be quite robust in the presence of receiver tracking errors. This is because the BP reconstruction is linearly weighted by the received amplitude. Regions of large tracking errors are typically associated with small SNR so that their contributions to the BP field are small. BP of CHAMP and SAC-C data also showed improved retrievals and generally reduced the negative refractivity bias with respect to numerical weather prediction models.

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References

1. G. Fjeldbo, A. J. Kliore, and V. R. Eshleman. The neutral atmosphere of Venus as studied with the Mariner V radio occultation experiments. *Astron. J.*, 76:123–140, 1971.
2. T. P. Yunck, G. F. Lindal, and C. H. Liu. The role of GPS in precise earth observation. In *IEEE Position, Location and Navigation Symposium*, Orlando, FL, Nov. 29–Dec. 2, 1988.
3. E. R. Kursinski, G. A. Hajj, J. T. Schofield, R. P. Linfield, and K. R. Hardy. Observing earth's atmosphere with radio occultation measurements using the Global Positioning System. *J. Geophys. Res.*, 102(D19):23429–23465, 1997.
4. G. A. Hajj, E. R. Kursinski, L. J. Romans, W. I. Bertiger, and S. S. Leroy. A technical description of atmospheric sounding by GPS occultation. *J. Atmospheric and Solar-Terrestrial Phys.*, 64(4):451–469, 2002.
5. C. Rocken, R. Anthes, M. Exner, D. Hunt, S. Sokolovskiy, R. Ware, M. Gorbunov, W. Schreiner, D. Feng, B. Herman, Y.-H. Kuo, and X. Zou. Analysis and validation of GPS/MET data in the neutral atmosphere. *J. Geophys. Res.*, 102(D25):29849–29866, 1997.
6. S. V. Sokolovskiy. Tracking tropospheric radio occultation signals from low Earth orbit. *Radio Sci.*, 36(3):483–498, 2001.
7. M. E. Gorbunov, A. S. Gurvich, and L. Bengtsson. Advanced algorithms of inversion of GPS/MET satellite data and their application to reconstruction of temperature and humidity. *Max-Planck Institute for Meteorology Technical Report (Hamburg)*, (211), 1996.
8. E. T. Karayel and D. P. Hinson. Sub-Fresnel-scale vertical resolution in atmospheric profiles from radio occultation. *Radio Sci.*, 32(2):411–423, 1997.
9. M. E. Gorbunov, A. S. Gurvich, and L. Kornblueh. Comparative analysis of radioholographic methods of processing radio occultation data. *Radio Sci.*, 35(4):1025–1034, 2000.
10. S. V. Sokolovskiy. Modeling and inverting radio occultation signals in the moist troposphere. *Radio Sci.*, 36(3):441–458, 2001.
11. M. E. Gorbunov. Radioholographic methods for processing radio occultation data in multipath regions. *Danish Meteorological Institute Scientific Report (Copenhagen)*, (01-02), 2001.
12. K. Igarashi, A. Pavelyev, K. Hocke, D. Pavelyev, I. A. Kucherjavenkov, S. Matyugov, A. Zakharov, and O. I. Yakovlev. Radio holographic principle for observing natural processes in the atmosphere and retrieving meteorological parameters from radio occultation data. *Earth Planets Space*, 52:893–899, 2000.
13. J. A. Kong. *Electromagnetic Wave Theory.* Wiley, New York, 2nd edition, 1990.
14. M. Levy. *Parabolic Equation Methods for Electromagnetic Wave Propagation.* The Institution of Electrical Engineers, London, 2000.